Modeling the Transport of Larval Yellow Perch in Lake Michigan

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Problem Statement

Yellow perch (*Perca flavescens*) is ecologically and economically important species in Lake Michigan that has suffered recruitment failures over the last decade (Francis et al., 1996). Causes for poor recruitment are not understood, but are believed to be a result of high mortality during the larval stage. The goal of this project is to begin exploring the effects of physical factors on recruitment variability of important Lake Michigan fishes in order to gain insight into the decline in the yellow perch populations and factors causing poor recruitment. In this project, we apply a model-based Langrangian approach that utilizes 3-D circulation and thermal processes, physiology and ecology of fish larvae, and trophodynamics for understanding recruitment dynamics in Lake Michigan specifically, and the other Great Lakes in general. In the initial set of numerical experiments we focus on the transport of larval yellow perch hatched in the area in southern Lake Michigan known for high concentrations of rocky habitat preferred by yellow perch spawners (Figure 1).

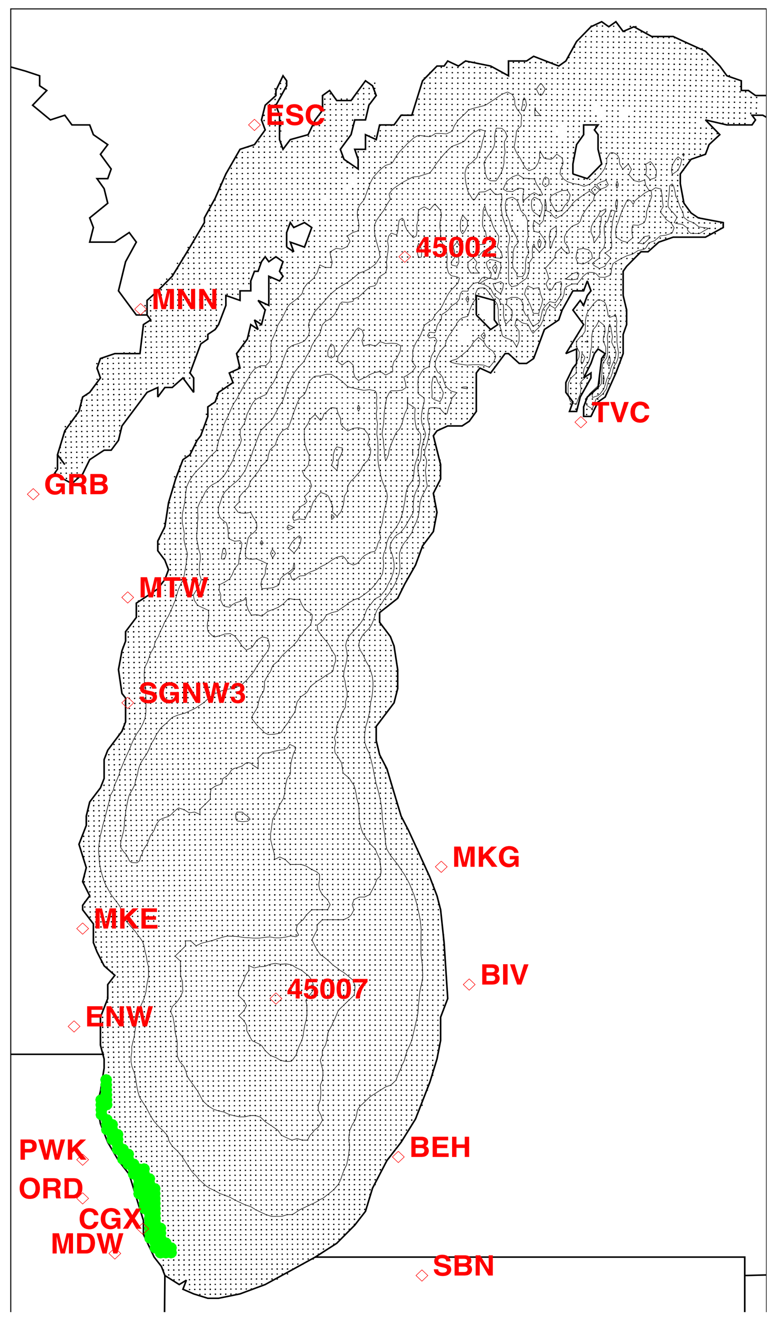

Figure 1. Numerical grid, bathymetry (isobaths every 50 m), and meteorological stations. Initial particles location in southern Lake Michigan is also shown.

Objectives

- Simulate larval yellow perch transport in Lake Michigan using 3D circulation model results.
- Develop coupled biophysical model to predict larval transport, larval growth, settlement and survival in 6 years (1998-2003).
- Explain inter-annual variability in larval survival and recruitment due to temperature and lake-wide circulation.

Approach

Hydrodynamic Model- Princeton Ocean Model (Blumberg and Mellor, 1987)

- Fully 3D nonlinear Navier-Stokes equations
- Free upper surface with barotropic (external) mode
- Baroclinic (internal) mode
- Mellor-Yamada turbulence model for vertical mixing
- Terrain following vertical coordinate (sigma-coordinate)

A 3-dimensional circulation model of Lake Michigan (Beletsky et al., 2006) is used to calculate lake circulation on a 2 km grid (Figure 1).

Particle Trajectory Model

- 3D model is based on the POM subroutine TRACE (by J.Berntsen).
- Particles are passive and neutrally buoyant.

Individual Based Perch Growth Model

Growth = Consumption - Losses
(Losses = Respiration, Egestion, Excretion)

- Determines length of time larvae can drift until settlement at 30-50 mm.
- Consumption is a function of temperature, larval weight and zooplankton prey density.
- Prey densities are constant in time and space (not enough information on spatial and temporal variability).
- No mortality.

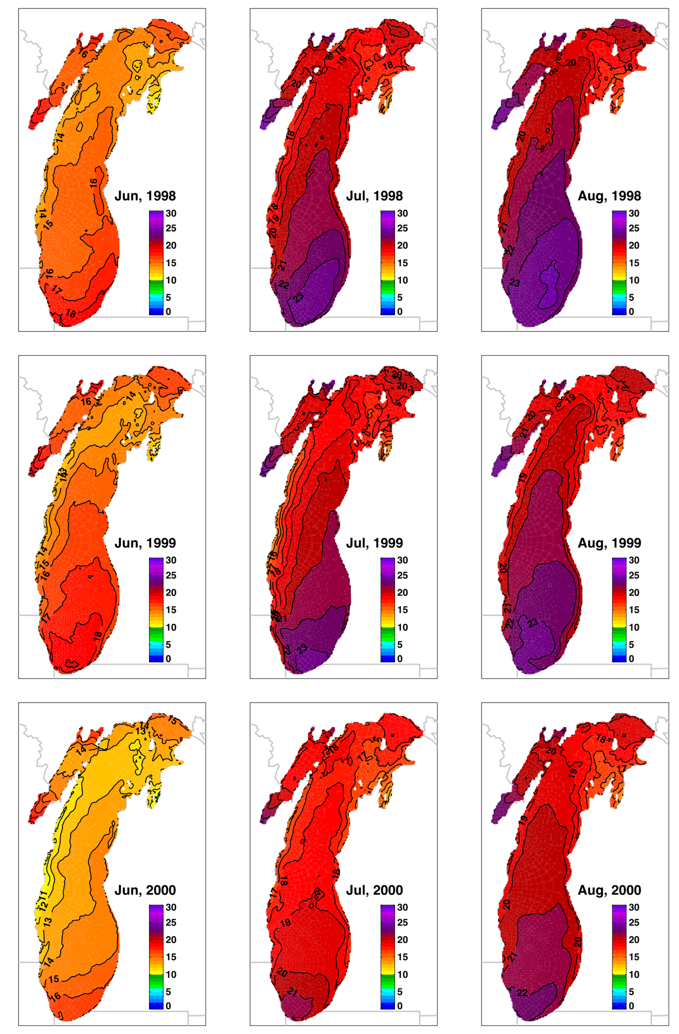

Figure 2a. Modeled lake surface temperature in 1998-2000.

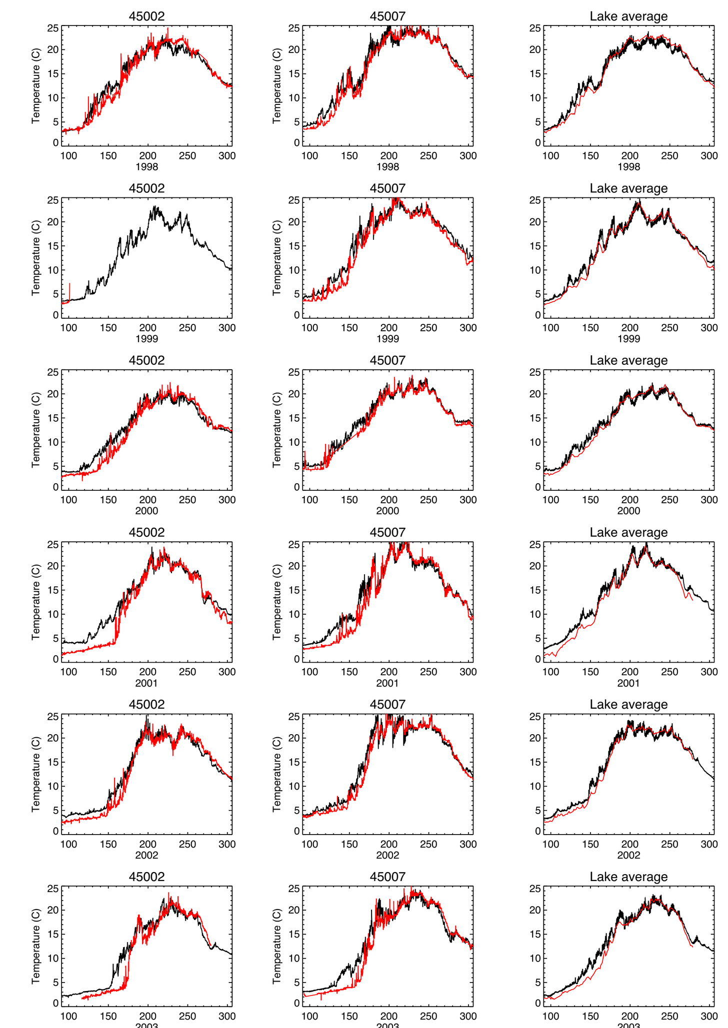

Figure 2b. Modeled (black) versus observed (red) lake surface temperature at 45002, 45007 and lake-averaged in 1998-2003.

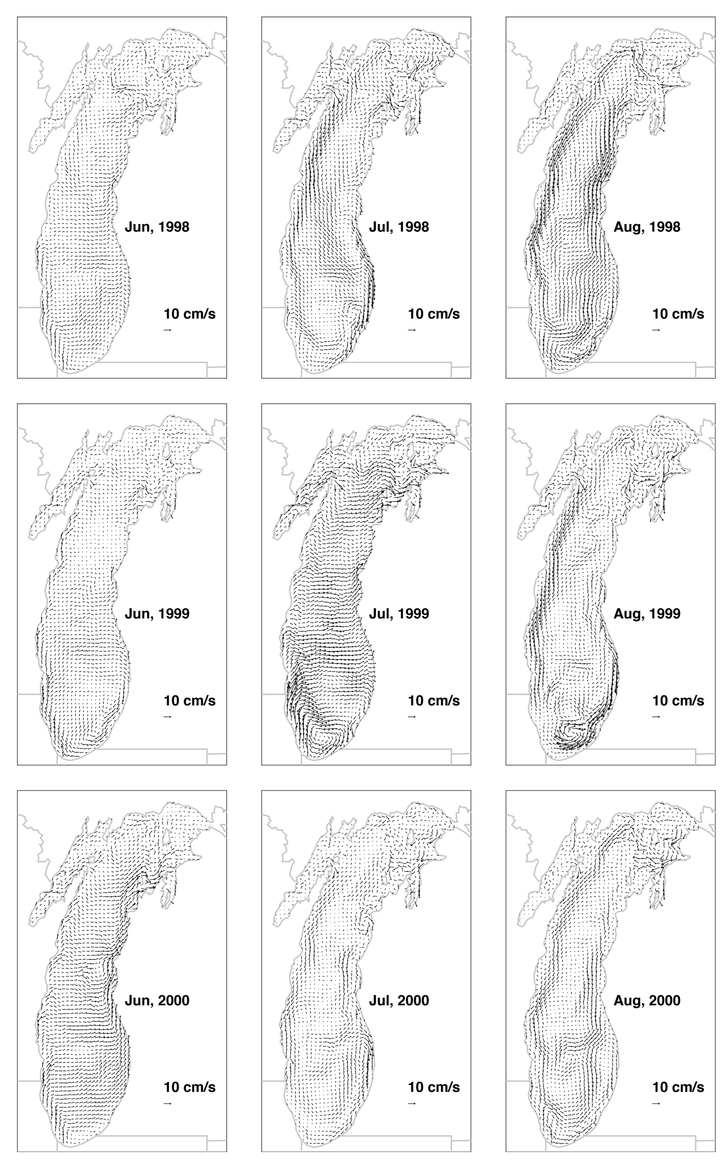

Figure 3. Surface currents in 1998-2000.

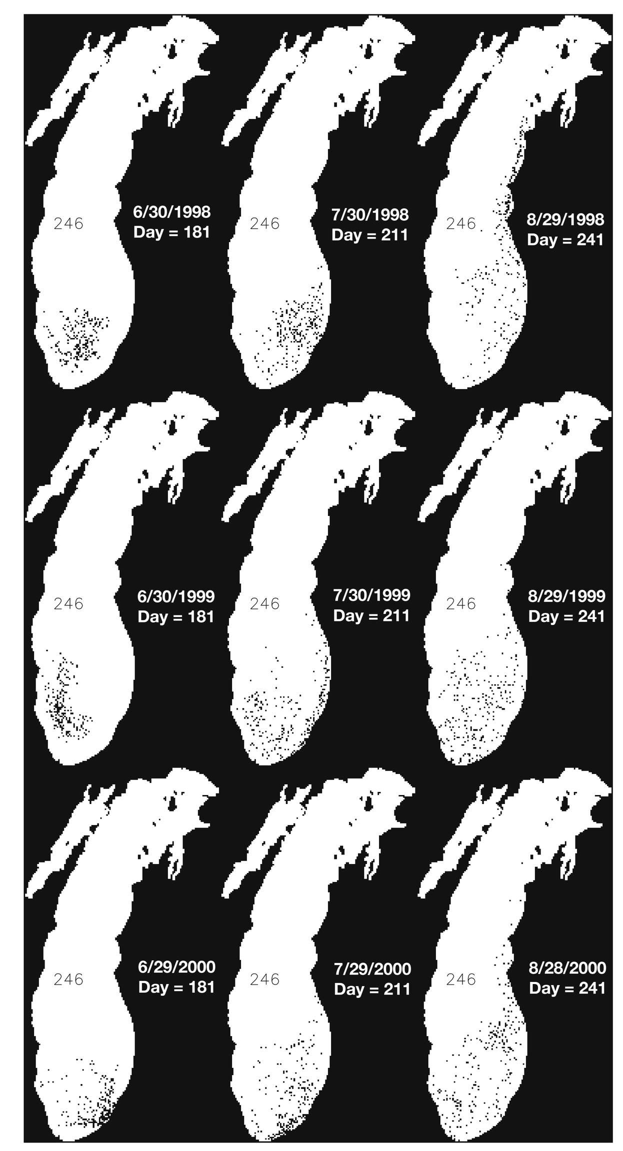

Figure 4. Particle transport in 1998-2000, total number of particles shown.

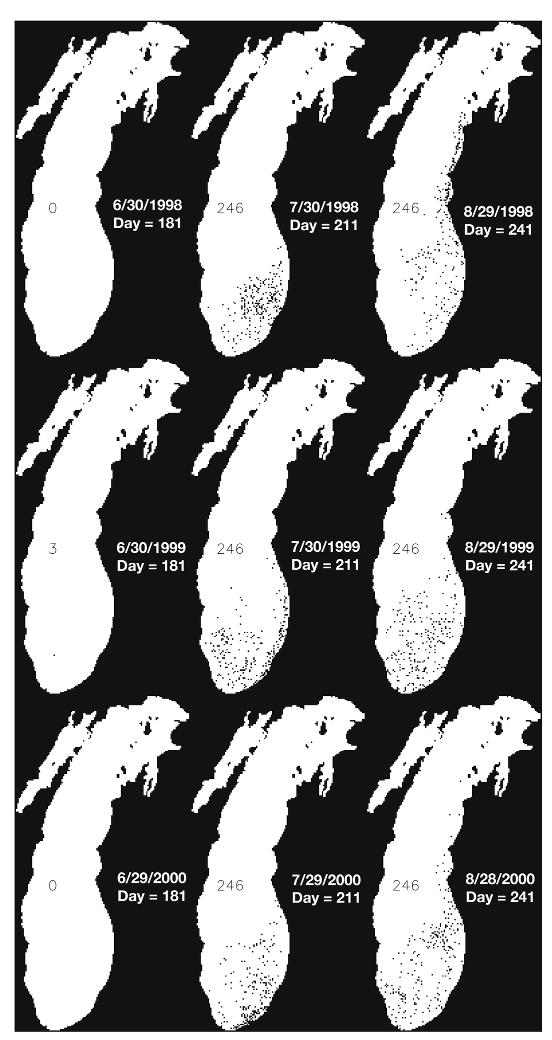

Figure 5. Larval transport and growth, Scenario 1 (see explanation in text). Total number of larvae reached 30 mm also shown.

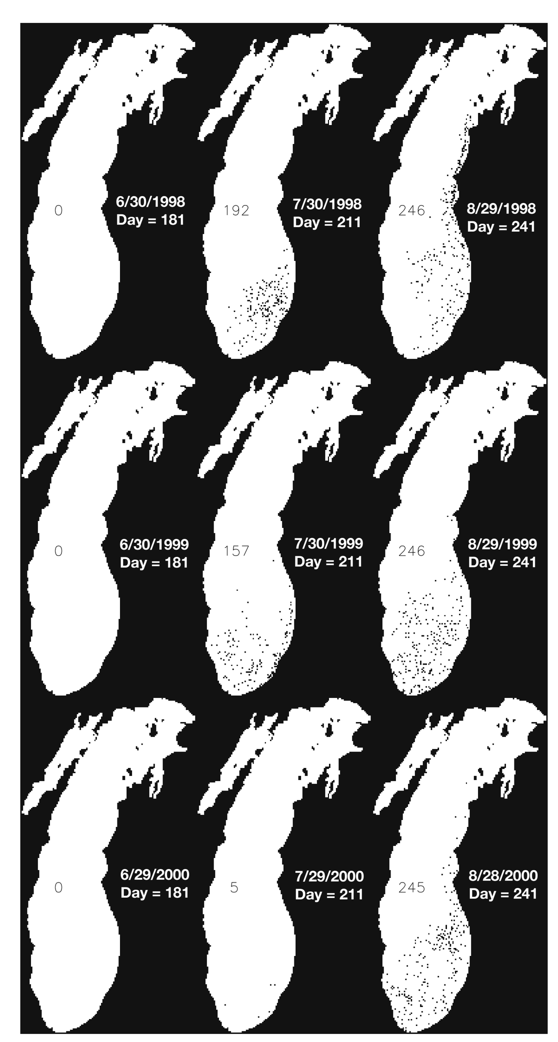

Figure 6. Larval transport and growth, Scenario 2 (see explanation in text). Total number of larvae reached 30 mm also shown.

Results

Physics

Monthly average surface temperature patterns for each summer in 1998-2000 are presented in Figure 2a. There is a general north-south temperature gradient seen in all months in all years. Another prominent feature of lake temperature patterns is a wind-driven upwelling at the west coast typical of summer conditions in Lake Michigan (Beletsky and Schwab, 2001). In southern Lake Michigan, surface temperature steadily increased from about 17 °C in June to 22 °C in July to 23 °C in August of both 1998 and 1999. In all summer months of 2000 lake surface temperature was about 1-2 °C lower which should have important implications on larval growth as will be shown in the next section. Model results were evaluated with surface temperature observations at NOAA buoys 45002 and 45007, and lake-wide satellite temperature observations (Figure 2b).

The circulation pattern in southern Lake Michigan often consisted of two gyres with the cyclonic gyre confined to the deep area and the anticyclonic gyre in the shallow southernmost area (Figure 3). During some months (August 1998, June and August 2000), a strong northward current from southern Lake Michigan penetrated the northern basin with significant implications for larval transport. The speed of mean surface currents varied from 10 to 20 cm/s.

In the particle trajectory model, 246 particles were released north of Chicago (Figure 1) at bathymetric depths of less than 10 m. Particles were distributed uniformly with depth: near the surface, at 1/3 and at 2/3 of a grid cell's depth. Particle model runs began on June first of each year (1998, 1999, and 2000) and ended in the end of August. Particle locations at the end of each month are shown in Figure 4. Because all particles were released in very shallow waters they have a tendency to stay relatively close to the surface (0-20 m). Overall, particle movement matches the monthly mean surface current pattern rather well: particles initially move offshore and then continue to circulate in southern Lake Michigan in an anticyclonic fashion. Under certain conditions (like a case of a particularly strong northward coastal current in August 1998) a significant number of particles escape the southern basin and penetrate the northern basin of Lake Michigan. The proximity of particles to shore at the end of the model run in August can also be critical for larval survival. Larvae about this time begin to metamorphose into their adult characteristics and move into adult habitat, which is near bottom and near shore. As model results show, in 1998 the number of particles reaching nearshore waters in August was significantly higher than in 1999 and 2000 which may provide a significant advantage for survival.

Biology

All larvae were assumed to have initial length of 6 mm at hatching. Movement and growth of larvae in the model were followed from hatching to 30-50 mm, the length at which they settle and become demersal; larvae metamorphose into juveniles at 20 mm, and by 30 mm take on the characteristics of adult fish. Growth rates and time to settlement were predicted assuming two different food availability scenarios. This was done by multiplying maximum consumption by 1.0 (Scenario 1) and 0.5 (Scenario 2). In all biological model runs we assumed that there is no spatial gradient in food (zooplankton) available for larval yellow perch. Locations of larvae which reached 30 mm length under the maximum consumption conditions (Scenario 1) are shown in Figure 5. No larvae reached 30 mm before the end of the first month except a small number in 1999. On the contrary, all larvae reached 30 mm by the end of the second month and therefore July and August locations match exactly those of Figure 4. In case of the reduced consumption scenario 2 (more typical of realistic Lake Michigan conditions) the situation changes dramatically. As expected, no larvae reached 30 mm by the end of June but by the end of July only a few larvae reached 30 mm in 2000 while in 1998 and 1999 more than 60% of larvae grew to their settlement length (Figure 6). This is undoubtedly the result of much cooler water temperatures in 2000 predicted by the hydrodynamic model and confirmed by surface temperature observations at the NDBC buoy 45007. Biophysical model performance was evaluated by comparing model results with independent observations of age-0 yellow perch abundance from 1998 to 2003 (Beletsky et al., 2007).

Conclusions

- First physical-biological model for larval fish in the Great Lakes was built.
- Model results show significant interannual variability in larval transport and growth.
- Model results are consistent with many recent observations in Lake Michigan.
- Physical model results can be used for other larval fish modeling in 1998-2003.